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Operation Cost Minimization of Droop-Controlled DC Microgrids Based on Real-Time Pricing and Optimal Power Flow

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Abstract—In this paper, an optimal power flow problem is formulated in order to minimize the total operation cost by considering real-time pricing in DC microgrids. Each generation resource in the system, including the utility grid, is modeled in terms of operation cost, which combines the cost-efficiency of the system with the demand response requirements of the utility. By considering the primary (local) control of the grid-forming converters of a microgrid, optimal parameters can be directly applied to the control of this level, thus achieving higher control accuracy and faster response. The optimization problem is solved in a heuristic way by using genetic algorithms. In order to test the proposed algorithm, a six-bus droop-controlled DC microgrid is used as a case-study. The obtained simulation results show that under variable renewable generation, load, and electricity prices, the proposed method can successfully dispatch the resources in the microgrid with lower total operation costs.

Index Terms—DC microgrids, demand response, economics, optimal power flow, genetic algorithm

I. INTRODUCTION

Increasing energy demand and environmental concerns have forced engineers to search for a solution to integrate more distributed renewable energy in an efficient, sustainable and reliable way. With distributed generation (renewable energy, energy storage and backup generation) and load, microgrid can work in both grid connected and islanded mode, and thus achieve this aim while having a minimal impact effects to the bulk grid.

While the concept of AC microgrids is relatively straight forward, DC microgrids is gaining more and more attention recently due to the following facts. Many distributed generation and storage systems, such as photovoltaics, fuel cells, batteries and supercapacitors present natural DC output. The voltage characteristic of many AC source generators, such as wind turbines and diesel generators, actually cannot match that of utility grid at their optimum operation point. All these mismatches require more energy conversion stages, i.e. AC-

DC and DC-AC conversions, which will lower the system efficiency [1], [2]. Moreover, more and more appliances, such as computers, LED lights, and electric vehicles, are in facts natural DC loads. Obviously, it is desirable to power DC loads with direct DC supply.

Most of the previous research on DC microgrids focus on the load sharing performed by the primary (local) control of DC microgrids, to ensure the stable operation of the system by using droop control or virtual impedance loops [3], [4]. However, with diverse sources of generation, to make the system not only stable but also cost-efficient during operation is of great significance [5]. Especially in the context of smart grid, microgrids are even expected to be acting as demand response entities.

Nevertheless, until now, few works have been done regarding the economic operation of DC microgrids. A way to improve the system efficiency by coordinating energy storage systems is provided in [6]. However, no other microgrid components except energy storage systems have been considered in this work. In [7], the authors provide a method to maximize the utility of the power produced in a microgrid by each load to improve the system efficiency. However, they did not take into account the retail electricity price in the demand response. In [8], a proposal of a coordinated control for the economic operation of a grid-connected dc microgrid was presented. However, no details about dispatch strategy for the tertiary control were given. In [9], researchers formulate a multi-objective optimization problem for a dc microgrid. Nevertheless, they did not consider the power losses in the electricity transmission, which may contribute up to 5% of the total power losses [6]. Further, an optimal demand response model is provided to minimize the total daily cost of electricity consumption for a household application, which needs to add the cost of other backup generation into the model for a microgrid application [10]. In contrast, [11] considers the distribution network of the microgrid, while optimizing the dispatch of the system through decomposing the problem into unit commitment and optimal power flow.

However, this approach does not consider the primary control of the microgrid, which requires the modification of the traditional power flow models due to the lack of slack bus, or else it will cause inaccuracy in the calculation results [12].

In this paper, an optimization problem is formulated to minimize the total operation cost with the aim to improve the system efficiency in the real-time pricing context. Each generation resources in the system, including the utility grid, is modeled into operation cost, which cannot only integrate the effects of the fuel price of the distributed generation systems, but also the system efficiency and demand response according to the real-time price information. By considering the primary control of the grid-forming converters of the microgrid into the power balance constraints, optimal variables can be applied directly to the primary control with high control accuracy and fast control response. The optimization problem is solved in a heuristic way based on genetic algorithms. In order to test the proposed algorithm, a six-bus droop controlled DC microgrid is chosen as a case study. The simulation results show that under variable renewable generation, loads and electricity prices, the proposed method can successfully dispatch the microgrid resources while minimizing the total operation cost.

II. SYSTEM OPERATION COST COMPOSITION

A. DC Microgrid Control Methodology

In order to connect DC components with DC voltages, while maintaining the interaction with the utility grid, one of the possible structures of a residential DC microgrid inside an AC grid is shown in Fig. 1. The renewable energy, i.e., wind and solar will provide free power to residential load, the utility grid, energy storage and backup generation system will compensate the power mismatches between renewable power and load, and the latter two make the islanded operation possible.

A hierarchical control paradigm is proposed in [3] for the microgrid, where the primary control uses the droop control while the upper lever modifying the parameter of the droop controller in order to manage the power in the system. The concept of basic droop control of the grid forming converter in the DC microgrid can be expressed as:

$$V_o = V_{ref,MG} - R_d i_o \quad (1)$$

where V_o is the voltage reference of the converter, $V_{ref,MG}$ is the reference voltage of the droop control, i_o is output current of the converter, and R_d is the virtual impedance value of the droop control.

III. SYSTEM OPERATION COST COMPOSITION

A. Utility Power Cost

By taking into account the utility grid as a generation unit, its operation cost is based on the price. With the development of “smart grid ready” technologies including smart-meters and bidirectional communications, customers can observe the real-time electricity price and to be involve more proactively into the contract with the power supplier in order to minimize the electricity cost [13]. Real time pricing is one of the new forms of agreement between the costumer and power supply, which

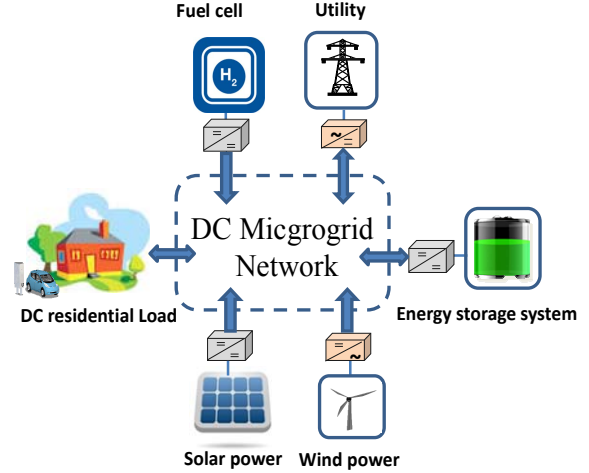


Figure 1. Structure of a residential DC microgrid.

will make possible real-time demand-response [14]. In the context of this mechanism, the operation cost of the power from utility in a corresponding control period ($C_{utility}$) can be modeled as:

$$C_{utility} = \begin{cases} \frac{\lambda_{buy} P_{utility}}{\Delta T}, & P_{utility} > 0 \\ \frac{\lambda_{sell} P_{utility}}{\Delta T}, & P_{utility} < 0 \end{cases} \quad (2)$$

where ΔT is the number of optimization cycles in an hour, λ_{buy} is the real-time utility electricity price, and λ_{sell} is the price of the electricity sold by the microgrid to the utility.

B. Energy storage cost

In this work, the operation cost of the energy storage is modeled according to the efficiency of the system. The major factors that influence its efficiency are charging rate and the state of charge (SOC) of the energy storage systems (ESS), which can be modeled as the following linear relationship [6]:

$$\eta_{ch} = a_{ch} - b_{ch} P_{ESS} \quad (3)$$

where a_{ch} and b_{ch} are both constants, and P_{ESS} is the measured power flow from the DC microgrid to the ESS in its output terminals.

This approximation considers only the charging rate, which is especially reasonable when dispatching in a quasi-instantaneous way, in which it has larger impact on the efficiency.

On the other hand, during the discharging mode, the efficiency in (3) can be rewritten as:

$$\eta_{dis} = a_{dis} + b_{dis} P_{ESS} \quad (4)$$

where a_{dis} and b_{dis} are both constants.

The operation cost can now be calculated depending on the charging ($P_{ESS} > 0$) or discharging ($P_{ESS} < 0$) modes as follows

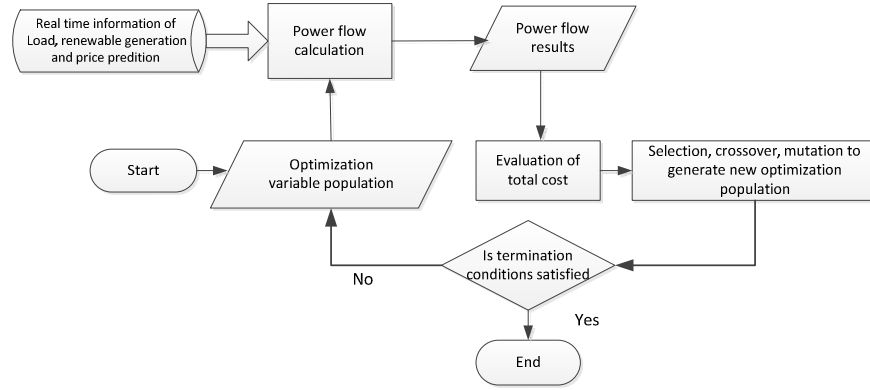


Figure 2. Flowchart of proposed optimal power flow algorithm

$$C_{ESS} = \begin{cases} \frac{\lambda_{buy}(P_{ESS} - \eta_{ch} P_{ESS})}{\Delta T}, & P_{ESS} > 0 \\ \frac{\lambda_{sell}(P_{ESS} - P_{ESS} / \eta_{dis})}{\Delta T}, & P_{ESS} < 0 \end{cases} \quad (5)$$

C. Fuel cell costs

The fuel consumed by the fuel cell generators can be modeled a quadratic relationship of the output power [15]. Hence, the operation cost of the fuel cell can modeled as follows

$$C_{FC} = \frac{a_{FC} P_{FC}^2 + b_{FC} P_{FC} + c_{FC}}{\Delta T} \quad (6)$$

being a_{FC} , b_{FC} , c_{FC} are all constants.

D. Transmission power loss cost

The transmission power loss does not belong to any generation but is the result of how power is dispatched, which is actually incorporated explicitly in the utility cost if accurate power flow model is added as constraints.

To emphasize it we can add this to the system cost model, which can be written as:

$$C_{loss} = \frac{\lambda_{buy} P_{loss}}{\Delta T} \quad (7)$$

E. Renewable energy cost

The fuel cost of renewable energy is of course free. To maximize the renewable energy generation, the operation cost in this study is considered as zero.

IV. PROBLEM STATEMENT

A. Proposed optimization function

The objective of this study is to minimize the total operation cost in one optimization cycle in the context of real pricing, in order to coordinate the renewable energy resources, energy storage system and backup generation system in a highly efficient way, while achieving demand response. Considering that in the microgrid each generation system type has only one unit, the total cost can be calculated through (2), (5), (6) and (7) as:

$$C_{total} = C_{utility} + C_{ESS} + C_{FC} + C_{loss} \quad (8)$$

In this way the economic benefits of the microgrid owner can be maximized. This objective can be written as:

$$\text{Minimize } C_{total}(x_i) \quad (9)$$

where optimization variables x_i are control variables of dispatchable units. Here we take the virtual impedance R_d of the grid forming unit as the optimization variable.

The constraints of the optimization problem includes the system constrains and those constrains from each generation system.

The first system constraints is the power balance of the system, which is can be written as:

$$P_{renewable} + P_{utility} + P_{FC} - P_{ESS} - P_{load} - P_{loss} = 0 \quad (10)$$

This equation is guaranteed by the convergence of power flow calculation using the method provided in [12].

The second system constraint considers the life cycle of the energy storage. We prohibit the case that energy storage is discharging, while power is feeding into the utility grid.

For each dispatchable unit, the power they dispatch should be maintained within their capacity limits, which can be expressed as:

$$P_{utility,min} < P_{utility} < P_{utility,max} \quad (11)$$

$$P_{ESS,min} < P_{ESS} < P_{ESS,max} \quad (12)$$

$$0 < P_{FC} < P_{FC,max} \quad (13)$$

All the inequity constraints are realized by adding a large value to the total cost as penalty.

B. Optimization

The methodology for solving aforementioned problem is based on optimal power flow using genetic algorithm (GA) [16], the flowchart of the algorithm is shown in Fig. 2.

The population of optimization variables is sent to the power flow process to get the power flow results which are taken to evaluate the total cost in the evaluation function. Based on the results in the evaluation function, GA will generate another generation of new population of the optimization variables, through selection, crossover and

TABLE I. LINE IMPEDANCE OF THE NETWORK

Line No.	From Bus	To Bus	R (pu)	length (m)
1	1	2	0.0058	200
2	1	4	0.0087	300
3	2	4	0.004	140
4	4	5	0.0058	200
5	5	6	0.0029	100
6	3	6	0.0043	150
7	2	3	0.0049	170

TABLE II. CAPACITY LIMITS OF EACH GENERATION

Generation	Utility	Energy Storage	Fuel Cell
Capacity limits (KW)	(-30,30)	(-30,30)	(0,30)

TABLE III. RENEWABLE GENERATION, LOAD AND REAL PRICE PROFILE

t	L1 [KW]	L2 [KW]	DG 1 [KW]	Price [cents/KWh]
1:00	10.84	20.39	43.66	19.86
2:00	9.35	17.74	50.00	18.79
3:00	8.78	16.67	35.02	18.64
4:00	8.67	16.36	18.35	18.79
5:00	8.61	16.26	15.21	19.68
6:00	9.24	17.30	24.47	21.67
7:00	12.03	21.76	31.59	34.62
8:00	15.58	28.59	39.08	25.05
9:00	15.07	27.64	42.95	24.06
10:00	13.00	24.41	43.31	25.47
11:00	13.14	25.43	44.93	23.85
12:00	13.41	25.83	45.96	23.97
13:00	12.98	24.30	42.41	21.97
14:00	12.60	23.39	33.15	20.54
15:00	12.44	23.40	26.48	20.37
16:00	13.28	25.05	37.20	19.44
17:00	16.50	30.51	46.24	20.56
18:00	22.77	41.35	47.76	24.11
19:00	26.50	47.42	47.98	29.84
20:00	26.02	46.42	41.92	27.39
21:00	24.17	43.41	37.26	25.11
22:00	22.11	40.27	23.63	22.88
23:00	18.31	33.90	25.93	20.04
24:00	14.60	27.52	29.12	20.18

mutation. The optimal results will be achieved when the algorithm converges.

V. CASE STUDY

In order to verify the model, a case study has been performed with a six-bus DC microgrid, which is shown in Fig. 3.

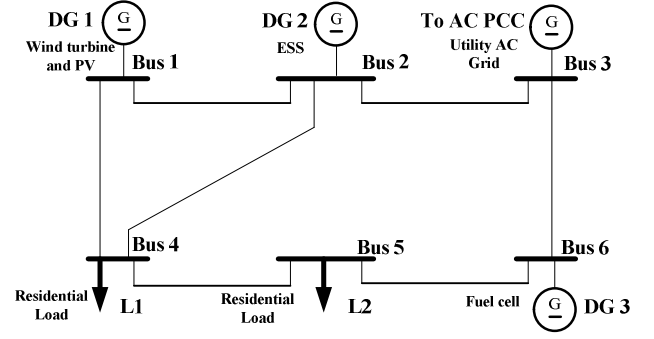


Figure 3. Six-bus DC microgrid

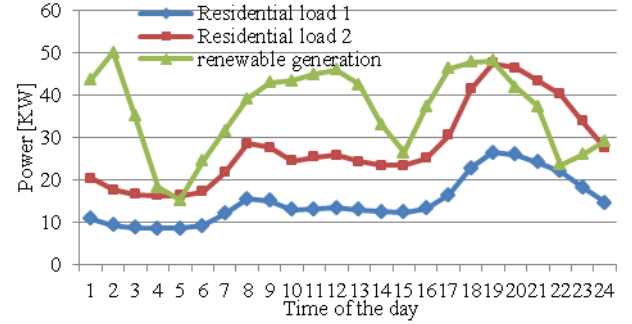


Figure 4. Load and renewable generation profile

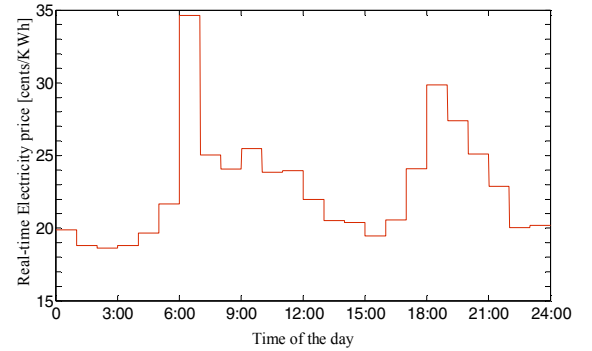


Figure 5. Real-time price profile

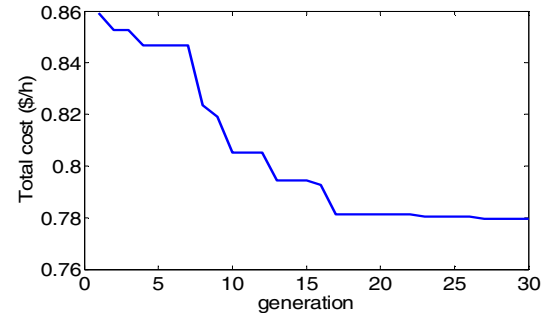


Figure 6. Convergence trace of the optimization for 22th hour.

The network parameters are given in Table I, and the generation capacity limits are given in Table II. The renewable generation, load profile and real-time price profile is given in the Table III, with the plot of these first two shown in Fig. 4 and the price profile shown in Fig. 5.

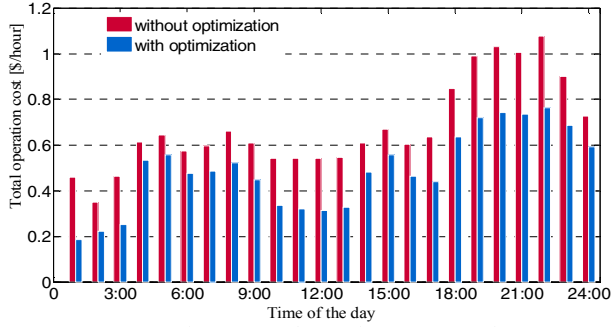


Figure 7. Total operation cost comparison.

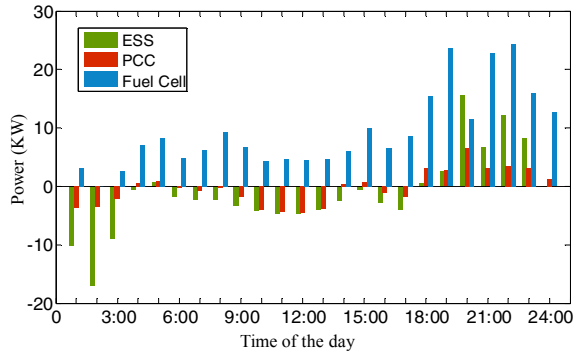


Figure 8. Optimal generation dispatch results.

The convergence of the proposed optimal power flow algorithm using GA is shown by the convergence trace of the optimization for a single day in Fig. 6.

The daily total operation cost using optimization is compared with the one without optimization in the Fig. 7, in which the virtual impedance for utility, fuel cell and energy storage is fixed as 0.01Ω , 0.3Ω and 0.3Ω respectively. The comparison shows that by optimal dispatching the resources, the total operation cost is reduced evidently. The dispatch results of each hour in a day is shown in Fig.8, no constraints are violated.

VI. CONCLUSIONS

In this work, in order to improve the system efficiency while participating in the demand response, an optimal power flow problem is formulated. The cost function considers not only the operation cost of microgrid owned components, but also the demand response requirements from the utility. The problem is solved in a heuristic method by using genetic algorithm. The case study results extracted from a six-bus DC microgrid shown that by adopting the optimized droop control parameters, the total operation cost of the system is effectively reduced.

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